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Adaptive Relay Scheme with Dual Protection Techniques Based On Differential and Alienation Principles

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Abstract: *Busbar Differential Relays May Operate Incorrectly Due To External Faults With Current Transformer (Ct) Saturation Extent. In This Paper, Two Different Techniques Are Suggested To Combine One Protective Scheme For Busbar Protection And Ct Saturation Detection. The First Proposed Algorithm Is Able To Perform Fault Detection, Faulty Phase Selection And Fault Location Discrimination Using Three Phase Alienation Coefficients In About A Half-Cycle Period. Each Alienation Coefficient Is Estimated Between The Input And Output Phase Current Signals Of Busbar. The Second Proposed Algorithm Is Based On The Fact That The Wave Shape Of The Ct Secondary Current Is Changed Significantly At The Beginning Instant And During Saturation. Based On This Feature, An Algorithm Which Uses Adaptive Differential Relay Characteristics For Avoiding Current Transformer (Ct) Saturation Effects Is Developed. The Alienation Coefficient Is Also Useful In Adapting The Relay Characteristics During Saturation Period Of Current Transformers To Avoid False Operation In The Event Of External Faults. The Later Method Is Able To Detect Even Small Ct Saturation Events. A Real 19.57 Kv Busbar Is Simulated Using Atp/Emtp And Matlab Packages For Evaluating The Performance Of The Proposed Algorithms. Obtained Simulation Results Demonstrate The Precise Operation Of The Both Proposed Algorithms In Different Types Of Faults.*

Keywords: *Fault Detection Ct Saturation Detection, Adaptive Busbar Differential Relay, Alienation Coefficient, Atp/Emtp Software, Matlab Package.*

I. Introduction

Busbar Is A Vital Part Of Power System Because It Links Incoming Circuits (Connected To Sources) To Outgoing Circuits Which Feed Loads. The Effect Of A Single Bus Fault Is Equivalent To Many Simultaneous Faults And Usually, Due To The Concentration Of Supply Circuits, Involves High Current Magnitudes. High-Speed Busbar Protection Is Often Required To Limit The Damaging Effects On Equipment And System Stability Or To Maintain Service To As Much Load As Possible. Differential Protection Is The Most Sensitive And Reliable Method For Protecting A Station Buses. The Phasor Summation Of All The Measured Current Entering And Leaving The Bus Must Be Equal Zero Unless There Is A Fault Within The Protective Zone. For A Fault Not In The Protective Zone, The Faulted Circuit Is Energized At A Much Higher Level, Near Ct Saturation Or With Varying Degrees Of Ct Saturation, Giving Rise To Possible High False Differential Currents. The Ct Does Not Saturate Suddenly But Reproduces The Primary Current Well For A Certain Time After Each Current Zero Crossing. During This Period, The Secondary Signal Provides Useful Information Regarding The Time-To-Saturation And The Degree Of Ct Saturation. Many Methods Are Used To Avoid The Ct Saturation Effects. Recently, Many Software Techniques Are Provided To Solve These Problems And Each Method Has Its Advantage And Disadvantage. Some Techniques Uses A Dc Component Equal And Opposite Of That In The Primary Circuit Generated By A Circuit Added To The Secondary Winding [1]. Other Techniques Used A Magnetization Curve And The Equivalent Circuit Of A Ct For Compensating Secondary Current Of Ct During Saturation. The Second Has Practical Difficulties, As It Depends On Ct Parameters /Characteristics And Secondary Burdens [2].

Also, The Artificial Neural Networks (Ann) Are Used In This Area. Ann Attempts To Learn The Nonlinear Characteristics Of Ct Magnetization And Restructures The Waveform Based On The Learned Characteristics. This Method Could Not Be Applied To Different Ct's Due To The Variations Of Ct's Saturation Characteristics And The Secondary Burdens [3]. Some Other Algorithms Prevent Relay Operation During Ct Saturation. This May Result In Longer Trip Times. A Method For Compensating The Secondary Current Of Ct's Is Based On The Ideal Proportional Transient Secondary Fault Current. A Portion Of Measured Secondary Current Following The Fault Occurrence Is Described Using Regression Analysis [4]. Another Method Utilizes Four Consequent Samples, During The Unsaturated Portion Of Each Cycle, For Solving A Set Of Equations To Obtain The Four Constants Of The Primary Fault Current Equation For Re-Constructing The Secondary Current During The Saturation Period. The Scheme Calculates The Correct Primary Time Constant By Repeating The Calculations Of The Algorithm Using Different Values Of Time Constant And Chooses The

Value That Gives The Smallest Error [5]. A Digital Technique For Protecting Busbars Presented In [6] Uses Positive- And Negative-Sequence Models Of The Power System In A Fault-Detection Algorithm. Another Method Called Current Phase Comparison Is Presented In [7], Which Can Achieve Reliable Busbar Protection With Minimum Ct Performance Requirements. A Model Parameter Identification Based Busbar Protection Principle Is Proposed In Paper [8]; An Inductance Model Can Be Developed When An Internal Fault Occurs On Bus. By Taking The Inductance And The Resistance Of The Model As The Unknown Parameters To Be Identified, The Equivalent Instantaneous Impedance And The Dispersion Of The Parameter Can Be Calculated. Utilizing Their Difference, The External Fault And The Internal Fault With Different Current Transformer (Ct) Saturation Extent Can Be Distinguished. The Application Of The Adaptivity Idea Is Indispensable To Assure Proper Operation Of The Protection For External Faults With Small Through Currents Accompanied With Ct Saturation Due To Dc Component. Paper [9] Developed An Adaptive Differential Protection Scheme Which Depends On Calculation Of The Initial Value (Amplitude) And Time Constant Of The Decaying Dc Component As Well As The Amplitude Of The Current Fundamental Frequency Component For The Time Instant Just After Fault Inception. Also, They Calculate The Expected Ct Saturation Period. These Estimates Are Performed For The Signals Generated From Each Ct Of The Protected Element. This Approach Also Needs The Ct Data And Reactance And Resistance Of The Network At The Fault Spot Which Are Used For The Estimation Of Ct Saturation Starting Time.

Before Discussing Our Suggested Protective Scheme, It Is Useful To Give A Glance Of The Operating Characteristics For One Of The Recent Busbar Differential Protections [10].

Conventional Differential Relay Characteristics

The Pickup Characteristic Of The Differential Protection Can Be Set In The Parameters For $I_d > I_{d0}$ (Where, I_{d0} = Pickup Value) And For The K_s Factor Which Considers The Linear And Non-Linear Current Transformer Errors. Figure 1 Shows That Differential Currents (I_d) Above The Set Characteristic Lead To Tripping [10]. The Relay Uses Multi-Slope Operating Characteristics; Where Each Differential Current Sample, Is The Summation Of The Corresponding Current Samples From Each Ct In The Protected Busbar Zone, As Shown In The Following Equation:

$$i_d(k) = \left| \sum_{j=1}^{N_c} i_{sj}(k) \right| \quad (1)$$

Where, N_c Is The Number Of Circuits Connected To The Busbar (I.E. The Number Of Cts In Busbar Differential Protection); $I_d(K)$ Is The Sampled Differential Current Waveform; $I_{sj}(K)$ Is The Sampled Secondary Current Waveform For Each Ct In A Circuit J (Where, J = 1 To N_c). And Each Restraining (Biasing) Current Sample Is The Summation Of The Absolute Values Of The Current Samples From Each Ct, As Shown In The Following Equation:

$$i_{bi}(k) = \sum_{j=1}^{N_c} \left| i_{sj}(k) \right| \quad (2)$$

Where, $I_{bi}(K)$ Is The Sampled Biasing Current Waveform. The Magnitudes Of The Fundamental Components Of $I_d(X)$ And $I_{bi}(K)$ Are I_d And I_{bi}, Respectively. They Are Calculated At Every Sample By Processing The Sequential And Samples Using The Fundamental Component Of A Full Cycle Discrete Fourier Transform (Dft).

The Operating Characteristic Of The Relay During Section Ab Is Described As Follows:

$$I_d > I_{d0} \quad (3)$$

The Operating Characteristic Of The Relay For Each Slope (K_s) During Section Bc Is Described As Follows:

$$I_d > I_{d0} + k_s I_{bi} \quad (4)$$

Where, K_s Is The Slope Of Each Operating Characteristic For Differential Relay.

The Differential Current (I_d) Is Used To Discriminate Between The External And Internal Faults. If The Magnitude Of The Differential Quantity I_d (K) During The Interval Follows The Fault Occurrence And Before The Ct Saturates Is Larger Than A Certain Predefined Threshold Value, An Internal Fault Is Detected. Otherwise The Fault Is Detected As An External. The External Fault May Enter Saturation Or Not. External Fault With Ct Saturation Is Defined As The I_d Exceeds The Predetermined Threshold Limit After A Delay Time (T_d) Of The Fault Occurrence [11].

Through-Out This Work, The Author Suggests A New Busbar Protection Scheme With Dual Protection Techniques; One Technique Performs Fault Detection, Faulty Phase Selection And Discrimination Between Internal And External Faults Using Three Phase Alienation Coefficients; And Another Technique With Adaptive Differential Relay Characteristics During Saturation Period Of Current Transformers. The Second Technique Uses The Alienation Concept For Evaluating The Degree Of Ct Saturation Extent Of The Distorted Secondary Current Signal In Cases Of External Faults. The Alienation Principle Is Also Useful To Select The

More Suitable Operating Characteristics According To Ct Saturation Degrees In Order To Avoid Incorrectly Relay Operation.

Basic Principles

In The Proposed Protective Scheme, The Three Phase Alienation Coefficients [12-16] Are Calculated For The Following Objectives:
(1) Fault Detection,
(2) Faulty Phase Selection
(3) Fault Location Determination,
(4) Ct Saturation Detection,
(5) Evaluation Of Ct Saturation Degree, And
(6) Adapting The Differential Relay Characteristics Of The Protected Busbar During Saturation Period For Current Transformers To Avoid False Operation In The Event Of External Faults.

Alienation Coefficients Calculation

The Variance Between Any Two Signals Is Defined As The Alienation Coefficient, Which Is Derived From Correlation Coefficient; Thus The Alienation Coefficient Is A Good Proposed Algorithm For Detecting Non-Similarity Between The Two Signals. Alienation Coefficient Calculated Between The Two Phase Currents Entering And Leaving The Busbar Can Recognize A Variance Between Them And To Operate In Response To It. Cross-Correlation Coefficient (R_a) Is Calculated Between Each Two Corresponding Windows Of The Two Sampled Currents (I_{a1} And I_{a2}) Entering And Leaving The Phase *"A"* Of Busbar, Where The Two Windows Are Shifted From Each Other With A Time Interval $H\delta t$. The Coefficient (R_a) Between The Two Signals (I_{a1} And I_{a2}) Is Given By Equation (5). Our Proposed Techniques Uses The Two Signals Shifted From Each Other When The Time Interval $H\delta t = 0$, Where $H = 0$ (H Is The Number Of Samples Between The Two Windows Which Are Shifted From Each Other And Δt Is The Time Interval Of One Sample). Also Cross-Correlation Coefficients (R_b *And* R_c) Are Given By Equations (6) And (7), Respectively [17].

$$r_a = \frac{\sum_{k=1}^{m} i_{a1}(k) i_{a2}(k+h\Delta t) - \frac{1}{m}\sum_{k=1}^{m} i_{a1}(k)\sum_{k=1}^{m} i_{a2}(k+h\Delta t)}{(\sqrt{\sum_{k=1}^{m}(i_{a1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{a1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{a2}(k+h\Delta t))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{a2}(k+h\Delta t))^2})} \quad (5)$$

$$r_b = \frac{\sum_{k=1}^{m} i_{b1}(k) i_{b2}(k+h\Delta t) - \frac{1}{m}\sum_{k=1}^{m} i_{b1}(k)\sum_{k=1}^{m} i_{b2}(k+h\Delta t)}{(\sqrt{\sum_{k=1}^{m}(i_{b1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{b1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{b2}(k+h\Delta t))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{b2}(k+h\Delta t))^2})} \quad (6)$$

$$r_c = \frac{\sum_{k=1}^{m} i_{c1}(k) i_{c2}(k+h\Delta t) - \frac{1}{m}\sum_{k=1}^{m} i_{c1}(k)\sum_{k=1}^{m} i_{c2}(k+h\Delta t)}{(\sqrt{\sum_{k=1}^{m}(i_{c1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{c1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{c2}(k+h\Delta t))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{c2}(k+h\Delta t))^2})} \quad (7)$$

Where,
R_a: The Cross-Correlation Coefficient Calculated Between Input And Output Current Signals (I_{a1} And I_{a2}) For The Phase *"A"* Of Busbar.
R_b: The Cross-Correlation Coefficient Calculated Between Input And Output Current Signals (I_{b1} And I_{b2}) For The Phase *"B"* Of Busbar.
R_c: The Cross-Correlation Coefficient Calculated Between Input And Output Current Signals (I_{c1} And I_{c2}) For The Phase *"C"* Of Busbar.
M: The Number Of Samples Per Window Used In The Algorithm.
$I_{a1}(K)$: The Summation Input Current Values At Instant K For Phase ''*A*'' Of Busbar.
$I_{a2}(K)$: The Summation Output Current Values At Instant K For Phase ''*A*'' Of Busbar.
$I_{b1}(K)$: The Summation Input Current Values At Instant K For Phase ''*B*'' Of Busbar.
$I_{b2}(K)$: The Summation Output Current Values At Instant K For Phase ''*B*'' Of Busbar.
$I_{c1}(K)$: The Summation Input Current Values At Instant K For Phase ''*C*'' Of Busbar.
$I_{c2}(K)$: The Summation Output Current Values At Instant K For Phase ''*C*'' Of Busbar.
The Alienation Coefficient (A_a), Calculated Between The Two Current Signals (I_{a1} And I_{a2}), Is Obtained From Cross-Correlation Coefficient (R_a) And It Is Given In Equation (8). Also, Alienation Coefficients (A_b *And* A_c) Are Given By Equations (9) And (10), Respectively [17].

$$A_a = 1 - (r_a)^2 \quad (8)$$

$$A_b = 1 - (r_b)^2 \quad (9)$$

$$A_c = 1 - (r_c)^2 \quad (10)$$

Where,
A_a: The Alienation Coefficient Calculated Between The Two Current Signals (I_{a1} And I_{a2}) For The Phase *"A"* Of Busbar.
A_b: The Alienation Coefficient Calculated Between The Two Current Signals (I_{b1} And I_{b2}) For The Phase *"B"* Of Busbar.
A_c: The Alienation Coefficient Calculated Between The Two Current Signals (I_{c1} And I_{c2}) For The Phase *"C"* Of Busbar.
Correlation And Alienation Coefficients Are A Dimensionless Quantities And It Does Not Depend On The Units Employed. The Value Of Cross-Correlation Is Between "-1" And "1", This Produces A Value Of Alienation Coefficient To Be Between "0" And "1". Three-Phase Current Signals Of Each Circuit (*J*), Connected To The Busbar, Are Obtained And Converted To Discrete Sampled Form By Atp/Emtp Program [18]. These Current Samples Of Each Phase Are Processed In Matlab Package [19] To Get An Alienation Coefficient For Each Phase. In This Paper, Two Different Techniques Are Suggested To Combine One Protective Scheme For Busbar Protection And Ct Saturation Detection. The First Proposed Algorithm Is Able To Perform Fault Detection, Faulty Phase Selection And Fault Location Discrimination Using Three Phase Alienation Coefficients. The Second Proposed Algorithm Is Based On The Fact That The Wave Shape Of The Ct Secondary Current Is Changed Significantly At The Beginning Instant And During Saturation. Based On This Feature, An Algorithm Which Uses Adaptive Differential Relay Characteristics For Avoiding Current Transformer (Ct) Saturation Effects Is Developed. The Alienation Coefficient Is Also Useful In Adapting The Relay Characteristics During Saturation Period Of Current Transformers To Avoid False Operation In The Event Of External Faults. The Calculations Of The Alienation Coefficients Are Processed For Each Two Corresponding Windows Of The Two Current Signals. The Selected Window (*M*) For The First Proposed Algorithm Is Quarter-Cycle To Get High-Speed Operation; And It Is One Cycle For The Second Proposed Algorithm. The Protective Scheme Determines Busbar Fault Type Whether Internal Or External To Make Relay Trip Or No Trip Decision, Respectively. The Scheme Performs Four Parallel Main Stages As Follows:
(1) Fault Detection And Faulty Phase Selection,
(2) Fault Location Discrimination (Internal Or External),
(3) Ct Saturation Assessment, And
(4) Adaptive Differential Relay Characteristics.

The Proposed Protective Scheme

Stage 1: Fault Detection And Faulty Phase Selection

The Flow Chart Of The First Proposed Algorithm Based On Alienation Coefficient For Fault Detection, Faulty Phase Selection And Fault Location Discrimination Is Shown In Figure 2. The Algorithm Has The Following Procedures:
(1) Read Discrete Sampled Of Three-Phase Secondary Current Signals For Three-Phase Current Transformers Of Each Circuit (*J*) Connected To The Protected Busbar (Obtained From Atp/Emtp Tool).
(2) Calculate Input And Output Current Values ($I_{a1}(K)$, $I_{a2}(K)$, $I_{b1}(K)$, $I_{b2}(K)$, $I_{c1}(K)$ And $I_{c2}(K)$) For Each Phase Of The Protected Busbar.
(3) Calculate Cross-Correlation Coefficient Between The Input And Output Current Signals For Each Phase Of Busbar As Given By Equations (11), (12) And (13).

$$r_a = \frac{\sum_{k=1}^{m} i_{a1}(k) i_{a2}(k) - \frac{1}{m}\sum_{k=1}^{m} i_{a1}(k) \sum_{k=1}^{m} i_{a2}(k)}{(\sqrt{\sum_{k=1}^{m}(i_{a1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{a1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{a2}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{a2}(k))^2})} \quad (11)$$

$$r_b = \frac{\sum_{k=1}^{m} i_{b1}(k) i_{b2}(k) - \frac{1}{m}\sum_{k=1}^{m} i_{b1}(k) \sum_{k=1}^{m} i_{b2}(k)}{(\sqrt{\sum_{k=1}^{m}(i_{b1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{b1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{b2}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{b2}(k))^2})} \quad (12)$$

$$r_c = \frac{\sum_{k=1}^{m} i_{c1}(k) i_{c2}(k) - \frac{1}{m}\sum_{k=1}^{m} i_{c1}(k) \sum_{k=1}^{m} i_{c2}(k)}{(\sqrt{\sum_{k=1}^{m}(i_{c1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{c1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{c2}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{c2}(k))^2})} \quad (13)$$

(4) Calculate The Alienation Coefficients (A_a, A_b *And* A_c), By Using The Obtained Cross-Correlation Coefficients (R_a, R_b *And* R_c), Respectively As Given Before In Equations (8), (9) And (10).

In Case Of No Internal Fault Condition, It Is Known That The Total Sum Of Input Currents Is Equal To The Total Sum Of Output Currents For Each Phase Of Busbar. Alienation Coefficient, Calculated Between The Input And Output Currents For Each Phase, Must Be Equal Zero Unless There Is A Fault Within The Busbar Protective Zone. The Proposed Technique Is Able To Accurately Identify The Condition Of Phase(S) Involved In All Ten Types Of Shunt Faults That May Occur On Busbar Under Different Loading Levels, Fault Resistances And Fault Inception Angles. Normally, The Value Of Cross-Correlation Coefficient Is "1" Because The Phase Shift, Between The Input And Output Current Signals, Is 0^0 In Case Of Ideal Normal Operation Or External Fault Without Ct Saturation ($R_a = R_b = R_c = 1$), Hence ($A_a = A_b = A_c = 0.0$). Whereas In Cases Of External Fault With Ct Saturation Or Internal Fault Located On Busbar, The Previous Rule Is Not Verified. As It Is Informed, No Ideal Operation Condition In Power System Protection Because Of The Linear And Non-Linear Errors Of Current Transformers. Thus, To Avoid This Drawback, The Proposed Algorithm Operation Under Healthy Condition Is Restricted By Alienation Coefficients Limits (A_x), Where The Selected Value Of $A_x = 0.05$.

(5) Fault Detection And Faulty Phase Selection Are Done According To The Following Sequences:

(A) If The Three-Phase Alienation Coefficients Values Are Greater Than A_x, Then The Fault Is Three-Phase And Internal.

- If $A_a > A_x$, $A_b > A_x$ *And* $A_c > A_x$, The Fault Is Three-Phase And Internal (A-B-C Fault).

(B) If The Two-Phase Alienation Coefficients Values Are Nearly Zero (Or Equal Or Less Than A_x), While The Third Phase Alienation Coefficient Is Greater Than A_x, The Fault Is Single Phase-To-Ground And Internal.

- If $A_a > A_x$, $A_b \leq A_x$, $A_c \leq A_x$, The Fault Is Single Phase- To-Ground And Internal (A-G Fault).
- If $A_b > A_x$, $A_a \leq A_x$, $A_c \leq A_x$, The Fault Is Single Phase-To-Ground And Internal (B-G Fault).
- If $A_c > A_x$, $A_a \leq A_x$, $A_b \leq A_x$, The Fault Is Single Phase- To-Ground And Internal (C-G Fault).

(C) If The Two-Phase Alienation Coefficients Values Are Greater Than A_x, While The Third Phase Alienation Coefficient Is Equal Or Less Than A_x, The Fault Is Internal And It May Be Phase-To-Phase Or Double Phase-To-Ground.

- If $A_a > A_x$, $A_b > A_x$, $A_c \leq A_x$, The Fault Is Internal And It May Be Phase-To-Phase (A-B Fault) Or Double Phase-To-Ground (A-B-G Fault).
- If $A_a \leq A_x$, $A_b > A_x$, $A_c > A_x$, The Fault Is Internal And It May Be Phase-To-Phase (B-C Fault) Or Double Phase-To-Ground (B-C-G Fault).
- If $A_a > A_x$, $A_b \leq A_x$, $A_c > A_x$, The Fault Is Internal And It May Be Phase-To-Phase (A-C Fault) Or Double Phase-To-Ground (A-C-G Fault).

(D) To Distinguish Between Double Phase And Double Phase-To-Ground Faults, A Fourth Alienation Coefficient Is Calculated Between The Two Faulted Phase's Currents For The Input (Or Output) Phase Currents Of The Protected Busbar). If The Value Of Alienation Is Nearly Zero, The Fault Is Phase-To-Phase (Because The Cross-Correlation Coefficient Calculated Between The Two Faulted Phase's Currents Is Equal -1).

- If $A_{ab} \leq A_x$ The Fault Is Phase-To-Phase And Internal (A-B Fault) Otherwise The Fault Is Double Phase-To-Ground And Internal (A-B-G Fault).
- If $A_{bc} \leq A_x$ The Fault Is Phase-To-Phase And Internal (B-C Fault) Otherwise The Fault Is Double Phase-To-Ground And Internal (B-C-G Fault).
- If $A_{ac} \leq A_x$ The Fault Is Phase-To-Phase And Internal (A-C Fault) Otherwise The Fault Is Double Phase-To-Ground And Internal (A-C-G Fault).

(E) If The Three-Phase Alienation Coefficients Values (A_a, A_b *And* A_c) Are Equal Or Less Than A_x, Then The Condition Is External Fault Or Normal Operation.

- If $A_a \leq A_x$, $A_b \leq A_x$ *And* $A_c \leq A_x$, The Fault Type Is External Or Normal Operation Condition.

(F) To Differentiate Between External Fault And Normal Operation Conditions, A Transition Is Detected For Each Phase Current Signal ($I_{s1}(K)$ And $I_{s2}(K)$) Of Busbar If $\Delta I > 20\% \, I_n$, Where I_n Is Busbar Nominal Current.

Stage 2: Fault Location Discrimination (External Or Internal Fault)

Briefly, Tripping/Blocking Action Of The Proposed Algorithm Relies On The Following Rules:

(1) Normal Operation Condition

- If $A_a \leq A_x$, $A_b \leq A_x$ *And* $A_c \leq A_x$ (For Each Phase Of Busbar), Then This Case Is Normal Operation Or External Fault Without Ct Saturation Condition (Where, A_x = 0.05 Is Selected) And The Scheme Holds Trip Signal To Low (0).
- $A_a \approx A_b \approx A_c \leq A_x$

(2) Internal Fault Condition

- If $A_a > A_x$, $A_b > A_x$ Or $A_c > A_x$ (For Any Phase Of The Protected Busbar), Then This Case Indicates To Internal Fault Condition Inside The Protective Busbar Zone. Hence The Faulted Busbar Must Be Isolated From The Remaining Power System, And The Scheme Sets Trip Signal To High (1).
- $T_{bb} = 0$ *Sec*, *Where*, T_{bb} = The Operating Time (In Seconds) For Busbar Protection Function.

(3) External Fault With Ct Saturation Condition

Consider The Period Of Free Saturated Portion (After Fault Inception) For The Distorted Secondary Current Is At Least One-Eighths (1/8) Cycle Because The Ct Secondary Current Does Not Saturates Suddenly.

- If $A_a \leq A_x$, $A_b \leq A_x$ *And* $A_c \leq A_x$ During The First One-Eighths (1/8) Cycle After Fault Inception (Because Of The Free Saturated Portion Of Secondary Current Signal) And $A_a > A_x$, $A_b > A_x$ Or $A_c > A_x$ After Time Instant Of Ct Saturation Beginning (Because Of The Distorted Secondary Current Signal), Then This Case Is External Fault With Ct Saturation Condition. In Other Words, The Alienation Coefficient Is Greater Than A_x During The Distorted Portions Of Current Signal And It Is Less Than A_x During Unsaturated Portions. This Event Makes The Scheme Holds Trip Signal To Low (0). Table 1 Shows The Limits Of Alienation Coefficients At Different Types Of Faults And The First Technique Action For Busbar Protection.

Stage 3: Ct Saturation Assessment

The Evaluation Of Ct Saturation Degree Is Necessary If The Adaptive Concept Is To Be Implemented In Practice To Get Required Improvement Of The Differential Protection Operation. Alienation Coefficient Is Used To Assess The Ct Saturation Degree; This Coefficient Is Calculated Between The Distorted Secondary Current Of The Faulted Circuit And The Summation Of The Other Secondary Currents For The Un-Faulted Circuits At Busbar Station In The Event Of External Faults With Ct Saturation Conditions. In Other Words, The Coefficient Is Estimated (For Each Phase) Between The Input And Output Phase Current Signals Of Busbar. As Stated Before, $I_{a2}(K)$, $I_{b2}(K)$ *And* $I_{c2}(K)$ Are The Summation Of Output Secondary Current Signals At Instant *K* For Three Phases ''A, *B And C*'' Of Busbar, Respectively. It May Be One Current Signal Obtained From One Ct Becomes Saturated (I.E. The Ct Connected To The Faulted Feeder); $I_{a1}(K)$, $I_{b1}(K)$ *And* $I_{c1}(K)$ Are The Summation Of Input Secondary Current Signals At Instant *K* For Three Phases ''A, *B And C*'' Of Busbar, Respectively. Each One Of Them Is The Summation Of The Un-Faulted Secondary Current Waveforms. As Mentioned Before, The Alienation Coefficient (A_s) Is Used To Evaluate The Degree Of Variance Between Each Two Current Signals ($I_{s1}(K)$ And $I_{s2}(K)$), Where A_s Denotes The Alienation Coefficient For Phase *S* (I.E. A_a, A_b *Or* A_c). So It Is Considered A Good Indicator For Estimation The Degree Of Ct Saturation Extent Of The Distorted Secondary Current Signal. In Addition, It Is Able To Calculate The Ct Saturation Period (T_s), I.E. Time Instants Of Saturation Beginning And End. The Greater The Degree Of Ct Saturation Extent, The Greater The Value Of Alienation Coefficient. The Second Proposed Algorithm Uses This Coefficient To Make An Adaptation For Differential Relay Characteristics During The Period Of Ct Saturation. The Flow Chart Of The Second Proposed Algorithm For The Differential Relay With Adaptive Characteristics Based On Alienation Coefficient Is Shown In Figure 3. The Procedures Of Adaptive Approach For The Differential Protection Characteristics Are As Follows:

(1) Read Discrete Sampled Of Three-Phase Secondary Current Signals For Three-Phase Current Transformers Of Each Circuit (*J*) Connected To The Protected Busbar,
(2) Set The Busbar Nominal Current, Pickup Differential Current, Minimum Slope And Alienation Coefficient Limit, I_n, I_{do}, K_s, A_x Respectively,
(3) Detect Fault, A Transition Is Detected For Each Phase Of Busbar If $\Delta I > 20\%\ I_n$, Where I_n Is The Busbar Nominal Current,
(4) Calculate The Differential And Biasing Currents, $I_d(X)$ And $I_{bi}(K)$, Respectively,
(5) Calculate The Three Phase Alienation Coefficients (A_a, A_b *And* A_c),
(6) Discriminate Between Internal And External Faults With/Without Ct Saturation Condtions,
(7) Evaluate The Ct Saturation Degrees By Using Alienation Coefficient In Case Of External Faults,
(8) Determine The Necessary Level Of Adaptation For Given Fault Case (Shifting Up Of The Differential Curve Or Slope Changing Of The Stabilizing Section),
(9) Execute The On-Line Adaptation Of The Differential Curve During The Saturation Period Of Current Transformers.

Stage 4: Adaptive Differential Relay Characteristics

In This Technique, The Author Suggests Constructing Similar Conventional Differential Relay But Improved By Making It Depends On The Estimation Of Ct Saturation Degrees Using Alienation Coefficients (A_s) And Selecting The More Suitable Operating Characteristics Slope (K_s) Of The Relay. So The Biased Differential Relaying Setting Is Adaptive Setting Based On Ct Saturation Degree. The Greater The Alienation Coefficient (A_s), The Greater The Operating Characteristic Slope (K_s) Of The Differential Relay. In Such Condition The Stabilizing Region Must Be Increased. The Author Suggests The Following Equation Which

Selects The Suitable Operating Characteristic (K_s) Based On Alienation Coefficient (A_s): Where, C_1 And C_2 Are Constants.

$$k_s \uparrow = c_1 + c_2 \times A_s \uparrow \qquad (14)$$

By Using Equation 14, The Technique Needs To Use Lookup Table For K_s And A_s-Values. The Lookup Table Determines The Most Suitable Operating Characteristic Slope (K_s) For Each Alienation Coefficient (A_s).

Assuming That The Relay Characteristic With K_s Varies From 0.1 To 1.0 Like Men's Other [10]. It Is Often More Convenient To Select The Operating Characteristic $K_s = 0.1$ For No Ct Saturation Extent $A_s = 0$ (Due To The Linear Errors Of Current Transformers) And The Operating Characteristic $K_s = 1$ Is Suitable For Saturation Degree $A_s = 1$(Due To The Linear And Non-Linear Errors Of Current Transformers). By Substituting These Data Into Equation 14, The Constants C_1 And C_2 Are Determined As 0.1 And 0.9, Respectively As Described In The Following Equation.

$$k_s = 0.1 + 0.9 \times A_s \qquad (15)$$

Now, The Adaptation Process Can Take Place By Applying Equation 15. This Is Done On-Line And The Operating Characteristic Curve (K_s) Is Selected According To The Value Of Alienation Coefficient (A_s), See Figure 4. Table 2 Illustrates Lookup Table Of Alienation Coefficients (A_s), Which Measure The Degree Of Ct Saturation Extent, And The More Suitable Operating Characteristics Slope (K_s) Of Differential Relay.

The Second Proposed Algorithm Uses The Alienation And Differential Protection Principles To Make Adaptive Logic. If No Ct Saturation Is Detected, The Alienation Principle Alone Is Capable Of Tripping The Busbar. If Ct Saturation Is Detected, Both The Alienation And Differential Principles Must Pickup In Order To Trip.

The Relay Coordination with Dual Protection Techniques

Protective Relay Coordination Is Necessary To Achieve Proper Fault Identification And Fault Clearance Sequence. In The Event Of Failure Of Primary Technique (Alienation) Meant For Isolating The Fault Within Its Primary Zone Of Protection, Backup Technique (Adaptive Differential) Must Operate After Providing For Sufficient Time Discrimination For The Operation Of Primary Technique. Hence, The Operation Of Backup Technique Must Be Coordinated With Those Of The Operation Of The Primary Technique. Relay Coordination Needs To Provide Suitable Settings Of Low Operating Time Where It Is Possible That The Settings Of Low Operating Time Can Positively Discriminate Between The Faults In The Primary And Subsequent Zones. This Is Essential To Ensure That The Settings Of Low Operating Time Will Not Act For Faults Outside Its Primary Protective Zone Bypassing The Needed Discrimination Between The Primary Technique To Which It Is A Backup.

Our Suggested Protective Scheme Processes The Dual Protection Techniques On The Basis Of And Logical Gate Rules. Table 3 Shows The Logical Rules For Processing The Dual Protection Techniques Of The Suggested Scheme. Figure 5 Shows The Relay Action Implemented Using And Logical Gate For The Dual Protection Techniques.

One Advantage For This Scheme Is That When An External Fault Occurs, The Second Proposed Algorithm Prevents The Relay Operation (Block Tripping) For A Delay Time (T_d) During The External Fault Period; But When An Internal Fault Following Directly An External Fault During The Period Of The Blocking Time (T_d), The First Proposed Algorithm Operates For Isolating The Internal Fault Which Occurs During This Period (T_d). Thus The Suggested Scheme Overcomes The Problem Of Longer Trip Time Which Is Popular In Most Conventional Differential Relays.

Power System Descriptions

The Single Line Diagram Of Power System Under Study Is Shown In Figure 6. The Simulated Power System Is Based On Realistic Power System Parameters. A Real 19.57 Kv Generator Busbar Is Simulated Using Atp/Emtp For Evaluating The Performance Of The Proposed Algorithms. The Rest Of Connected System Parameters Are Obtained From A Part Of The Egyptian 500 Kv Unified Network [20] And Are Given In Table 4.

Simulation Results

To Implement The Present Protective Scheme With Dual Protection Techniques, The Studied Power System Configuration Was Simulated By Using Atp Software. The Generated Three Phase Current Signals Of All Feeders Connected To The Protected Busbar (Bb_1) Are Taken From The Protective Current Transformers Of Busbar Zone. The Relay's Cts Orientation Is Built For Busbar Protection. A Pure Resistive Ct Burden Is Assumed In The Presented Studies Cases. The Procedures Of The Two Protection Algorithms (Based On Alienation Coefficients) Are Implemented In The "M File" Of Matlab Package. In Order To Examine The Performance Of The Suggested Scheme Under Different Types Of Faults, A Wide Range Of Simulation Cases Were Processed And Analyzed. The Simulation Case Studies Are Processed To Determine The Faulty Phases, Discriminate The Fault Location, Detect Ct Saturation And Adapt The Characteristics Of Differential Relay During Saturation Period Of Current Transformers. Hence These Cases Are Examined Under Effects Of Different Pre-Fault Load Levels, Fault Resistances, Fault Inception Angles, Fault Locations, Faulty Phases And Various Ct Secondary Burdens Which Occur In The Simulated Power System. An Internal Fault (F_1) Was Considered Inside The Busbar Protective Zone Assuming That Short Circuit Is Not Resistive. Another Fault (F_2) Was Considered Outside The Busbar Protection Zone As Shown In Figure 6. The Current Signals, From Atp Software, Generated At Sampling Rate Of 100 Samples Per Cycle, This Gives A Sampling Frequency Of 5 Khz. The Total Simulation Time Is 0.2 Sec (I.E. The Total Number Of Samples Is 1000). The Time Instant Of Fault Inception Is 0.042 Sec (At Sample 210 From The Beginning Of Simulation Time). The Developed Protective Scheme Was Applied By Calculating The Alienation Coefficient Between Each Two Corresponding Windows (M) For Input And Output Phase Current Signals Of The Protected Busbar, Where Protective Relays Would Normally Be Installed. The Applied Window For The First Algorithm Is A Quarter-Cycle (*M = 25 Samples/Cycle*); And It Is One Cycle (*M = 100 Samples/Cycle*) For The Second Algorithm.

Case 1: External Slg Fault With Ct Saturation (R_b = 30 Ω For Ct Phase A Of Load-1)

The Operating Conditions Of The Simulated Power System Are Shown In Table 5. In This Case, The Fault Type Is External Single Line-To-Ground Fault (*A-G*) At Point *F2* (See Figure 6). The Burden Resistance (R_b) For Phase "*A*" Current Transformer Of Load "1" Feeder Is 30 Ω While The Burden Values For The Remaining Cts Are 0.5 Ω. Figures 7-10 Show The Simulation Results For Case 1. Figures 7(A-C) Present The Three-Phase Secondary Current Signals Of The Three Feeders (Generator, Load "1" And Load "2"), Respectively. The Three-Phase Current Signals During The Fault Interval Are Higher Than The Pre-Fault Currents And With High Dc Component (I.E. The Fault Current Is Greater Than $1.2i_n$). The Main Causes For The Fault Accompanied With Severe Ct Saturation Are The Large Magnitude Of Short Circuit Current, High Dc Component And High Burden Of The Current Transformer. The Saturation Condition Appears During The First Cycle (From The Fault Beginning) For Case 1. This Is Due To The Higher Burden Of The Current Transformer Of Phase "*A*". Figures 7(D-F) Show The Input And Output Current Signals Of Each Phase For The Protected Busbar, Respectively. Figures 8(A-C) Show The Calculated Differential Current Signal (I_{ds}) And The Signal Of Conventional Characteristic Equation $[I_{d0} + 0.1 \times I_{bis}]$ Based On The Biasing Current Signal (I_{bis}), And The Pickup Value Of Differential Current (I_{d0}) Of Each Phase (S) For The Protected Busbar, Respectively, (The Selected Characteristic Slope Is K_s = 0.1). The Three-Phase Alienation Coefficients A_a, A_b *And* A_c Are Shown In Figure 9(A-C), Respectively, Where The Selected Window For Calculation Of The Three Coefficients Of The First Algorithm Is A Quarter-Cycle (*M = 25 Samples/Cycle*). The Value Of A_a Are Equal And Close To Zero Before Fault Inception. From The Instant Of Fault Start To The Instant Of Ct Saturation Start, A_a Is Also Close To Zero. The Coefficient A_a Becomes Greater Than 0.25 During The Saturated Portion And It Is Less Than 0.05 During The Unsaturated Portion Of Each Cycle For Current Signal; While A_b And A_c Are Nearly Zero Before Fault Start And Through The Fault Interval. A_a Confirms That There Is Saturation Condition For One Current Signal Of Phase *A (*Because $A_a > A_x$ After A Certain Time Of The Fault Inception*)*; But A_b And A_c Prove That No Ct Saturation Condition For The Two Current Signals Of Phases *B* And *C (*Because $A_b \leqslant A_x$ *And* $A_c \leqslant A_x$ During The Fault Interval*)*. Figures 10(A-C) Shows The Estimated Three-Phase Alienation Coefficients (A_a, A_b *And* A_c), Respectively, Where The Selected Window For Calculation Of The Three Coefficients Of The Second Algorithm Is One Cycle (*M = 100 Samples/Cycle*). Figures 10(D-F) Show The Suitable Operating Characteristics Slope (K_{sa}, K_{sb} And K_{sc}) For Three Phases Of Adaptive Differential Relay, Respectively. These Slopes Are Obtained From The Following Proposed Equation Based On The Calculated Three-Phase Alienation Coefficients: $K_s = 0.1 + 0.9 \times A_s$. Figures 10(G-I) Show The Calculated Differential Current Signal (I_{ds}) And The Signal Of Adaptive Characteristic Equation $[I_{d0} + K_{ss} \times I_{bis}]$ Based On The Biasing Current Signal (I_{bis}), The Phase Alienation Coefficients (A_s) *And* The Pickup Value Of Differential Current (I_{d0}) Of Each Phase (S), Respectively. From The Above Simulation Results, It Is Clear That The Alienation Coefficient Values From Fault Initiation To Ct Saturation Start Are Good Supervisor To Determine The Fault Location Zone (External Or Internal Fault); And It Is Able To Differentiate External Faults With/Without Ct Saturation Condition And Estimates The Ct Saturation Period. In This Case, The Fault Location Zone Is External *Slg* Fault And The Faulted Phase Is *(A*-G) Because Of Alienation Coefficient Value A_a Is Close To Zero During The Free Saturated Portion Of Current Signal; And It Is Greater Than 0.25 During Saturation Period While A_b And A_c Are Nearly Zero During The Periods Of Normal Operation And The Fault Conditions. The Located External Fault Condition Makes The Scheme Holds Trip Signal To Low (0) As Shown In Figure 10(J).

Case 2: Internal 3-Lg Fault Without Ct Saturation (R_b = 0.5 Ω For Each Ct)

This Case Studies The Performance Of The Proposed Scheme In The Event Of Internal Three Phase-To-Ground Fault Condition *(A-B-C-G*). The Operating Conditions Of The Simulated Power System Are Shown In Table 5. Figures 11-13 Show The Simulation Results For Case 2 (In Case Of Internal Three Line-To-Ground Fault Without Ct Saturation, Where R_b = 0.5 Ω For Each Ct). Figures 11(A-C) Present The Three-Phase Secondary Current Signals Of The Three Feeders (Generator, Load "1" And Load "2"), Respectively. The Three-Phase Current Signals During The Fault Interval Are Higher Than The Pre-Fault Currents And With High Dc Component (I.E. The Fault Current Is Greater Than $1.2i_n$). Figures 11(D-F) Show The Input And Output Current Signals Of Each Phase For The Protected Busbar, Respectively. Figures 12(A-C) Show The Calculated Differential Current Signal (I_{ds}) And The Signal Of Conventional Characteristic Equation $[I_{d0} + 0.1 \times I_{bis}]$ Based On The Biasing Current Signal (I_{bis}), And The Pickup Value Of Differential Current (I_{d0}) For Each Phase (*S*) Of The Busbar, Respectively, (The Selected Characteristic Slope Is K_s = 0.1). The Three-Phase Alienation Coefficients A_a, A_b *And* A_c Are Shown In Figure 13(A-C), Respectively, Where The Selected Window For Calculating The Three Coefficients Of The First Algorithm Is A Quarter-Cycle (*M = 25 Samples/Cycle*). The Values Of A_a, A_b *And* A_c Are Equal And Close To Zero Before Fault Inception. At Fault Start And Duration, They Are Greater Than 0.2. From The Above Results, It Is Clear That The Values Of Three Alienation Coefficients At Fault Initiation Are Good Detector To Determine The Faulted Phases And The Zone Of Fault Location; Their Values Are Closely To Zero In Case Of Normal Operation And They Are Greater Than A_x (Where, A_x = 0.05) In Case Of Internal Fault Condition. In This Case, The Fault Location Is Internal And The Faulted Phases Are *A*, *B And C*. When The Fault Is Internal, A Trip Signal Is Sent For Busbar Isolation (From The Rest Of Connected Power System) By Opening All Cbs Of All Feeders Connected To The Faulted Busbar; The Scheme Sets Trip Signal To High (1) As Shown In Figure 13(D).

Relay Performance Evaluations

From The Obtained Simulation Results, It Is Clear That The Proposed Scheme With Dual Protection Techniques Based On Alienation Algorithm Succeeded In Detecting And Differentiating Between External And Internal Faults Occurring In The Protective Busbar Zone Besides Identifying The Faulted Phase(S). In Addition, The Scheme Has Adaptive Characteristics For Differential Protection During The Saturation Period Of Current Transformers. The Adaptation Principle Is Based On The Estimation Of Ct Saturation Degrees Which Are Evaluated By Alienation Coefficients. The Simulation Results Of The Developed Adaptive Busbar Differential Protection Scheme Proved Much Better Relay Performance When Compared To Traditional Relay Version Without Adaptation; Where The Results Indicate That The Protective Scheme Is Very Effective In Preventing False Tripping During External Faults With Various Ct Saturation Extent; This Is Controlled By Selecting The More Suitable Operating Characteristics Of Adaptive Differential Relay. The Operating Characteristic Slope (K_s) Depends On The Degree Of Ct Saturation Extent Measured By Alienation Coefficient (A_s). It Is Clear Evident That The Application Of The Adaptivity Idea For Busbar Protection Based On Alienation Concept Is Useful To Assure Proper Operation Of Relay In Cases Of External Faults With Various Degrees Of Ct Saturation. A Reliable, Stable, And Efficient Scheme Has Been Presented For Discriminating Different Types Of Faults.

Though The Proposed Techniques Are Developed And Examined For Busbar Current Differential Application, These Techniques Can Be Adapted For Use In Other Differential Protection Applications Such As, Generators, Power Transformers, Motors, Cables, And Short Transmission Lines.

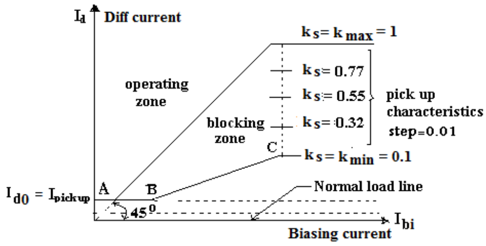


Figure 1 The Conventional Operating Characteristics Of Percentage Differential Relay.

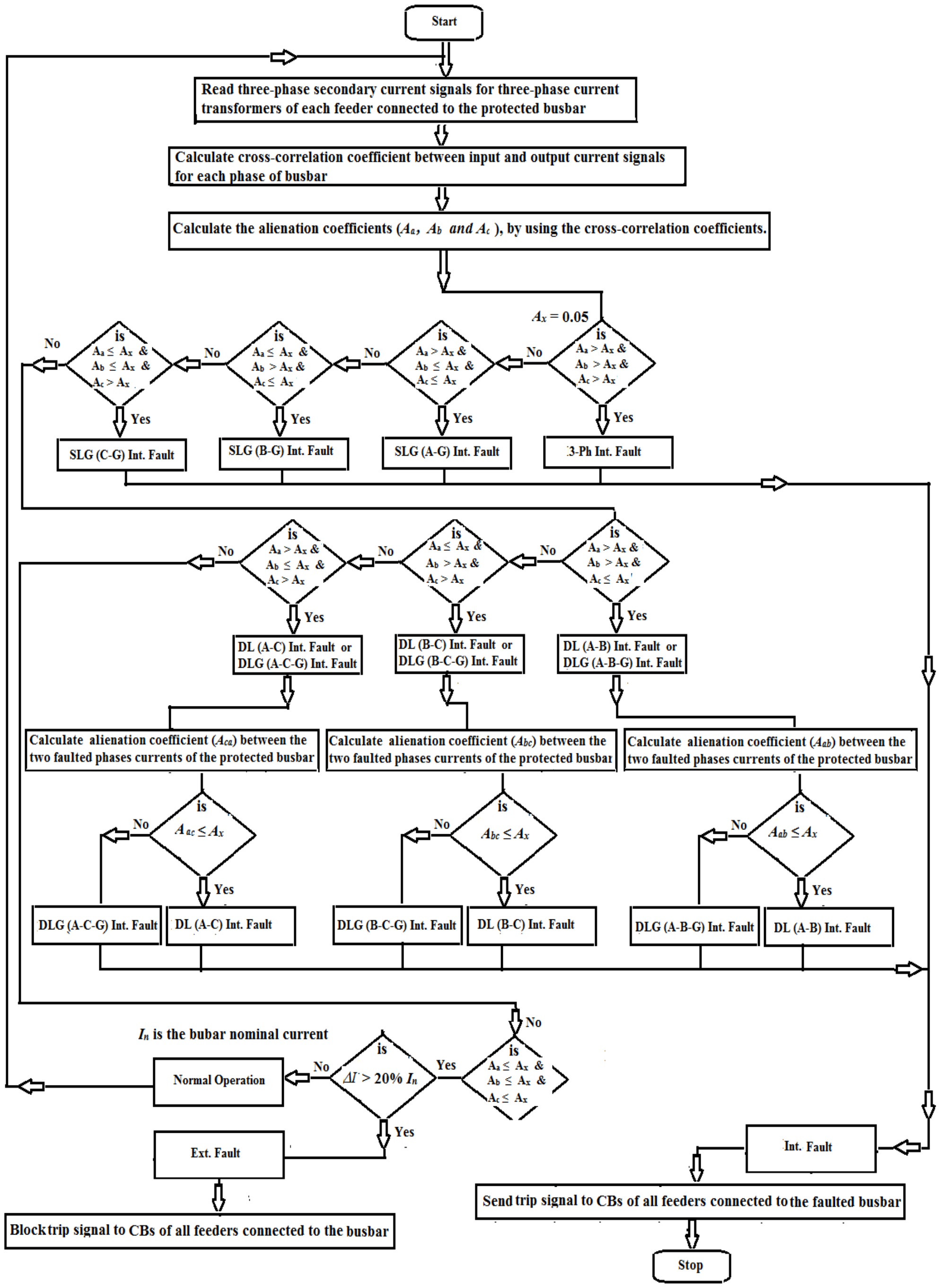


Figure 2 Flow Chart For Fault Location Discrimination Algorithm Based On Alienation Coefficients (Technique 1).

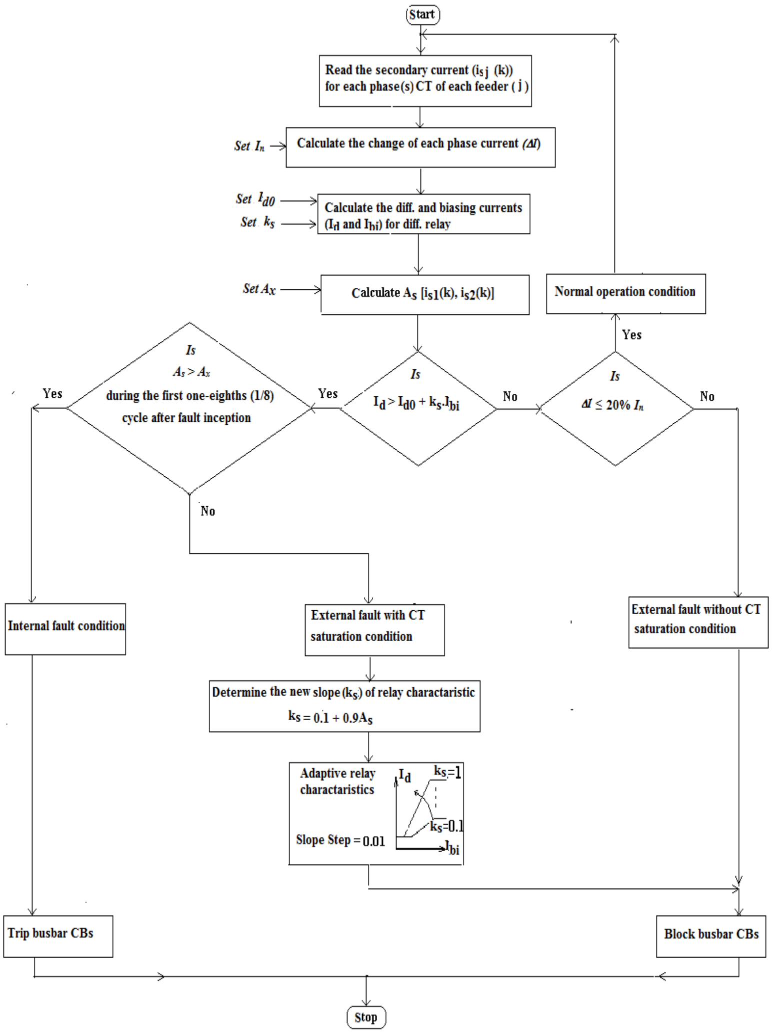


Figure 3 Flow Chart For Adaptive Differential Relay Characteristics Based On Alienation Coefficients (Technique 2).

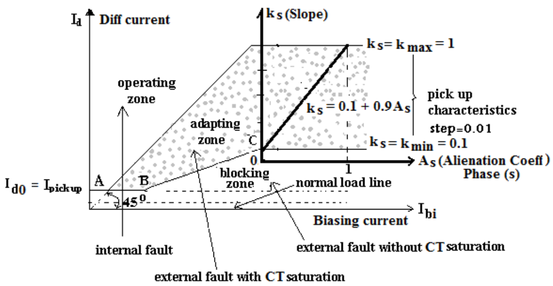


Figure 4 The Operating Characteristics Of Adaptive Differential Relay Based On Alienation Coefficients (Technique 2).

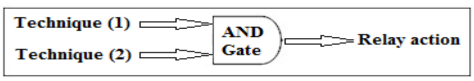


Figure 5 The Relay Action Implemented Using And Logical Gate For Processing The Dual Protection Techniques.

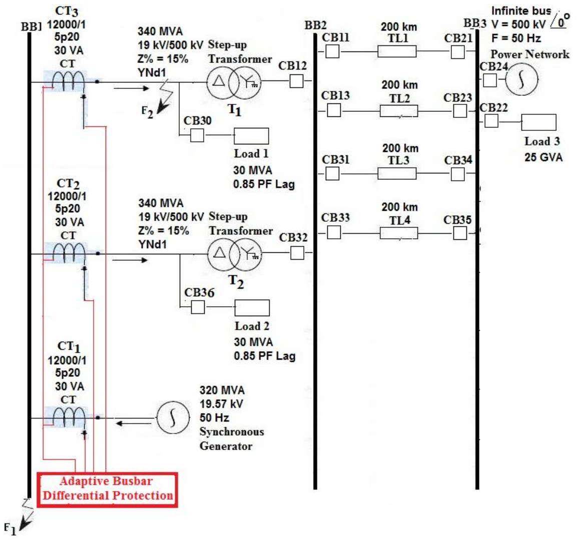
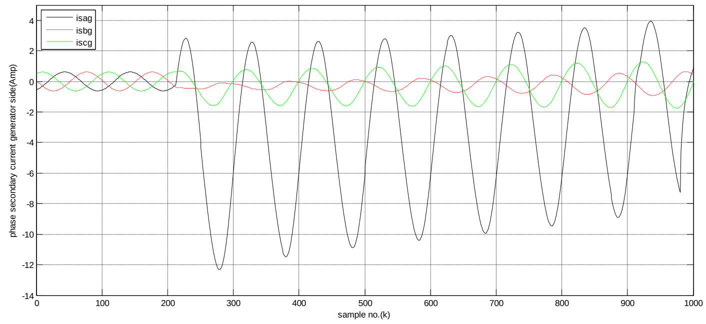
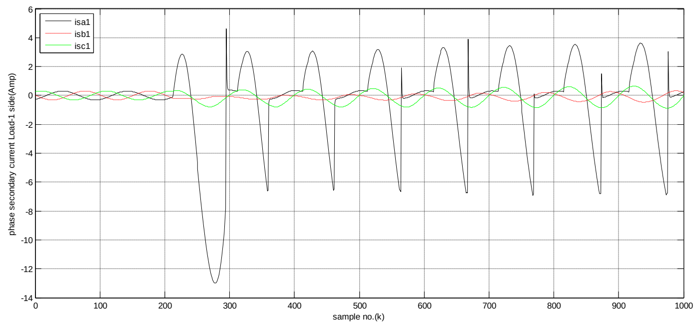


Figure 6 Single Line Diagram For The Studied Power System.

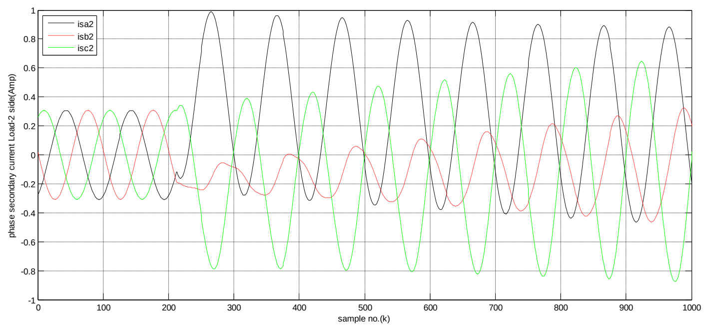
Case 1: External Single Line-To-Ground Fault With Ct Saturation (R_b = 30 Ω For Ct Phase A Of Load-1)



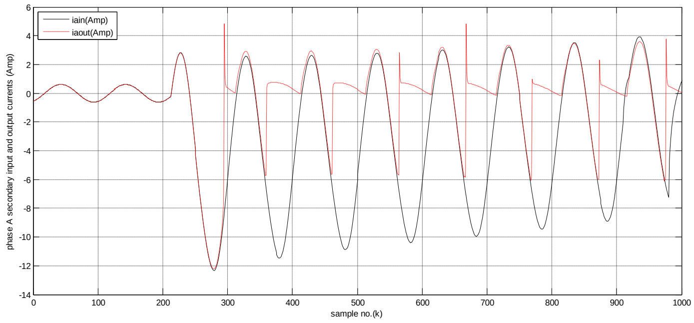
(A) Three Phases Instantaneous Secondary Currents Of Generator Feeder.



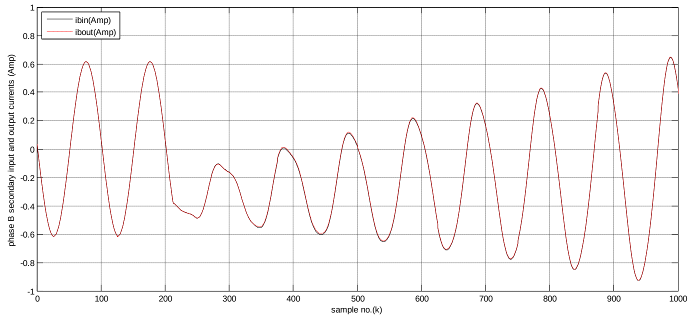
(B) Three Phases Instantaneous Secondary Currents Of Load 1 Feeder.



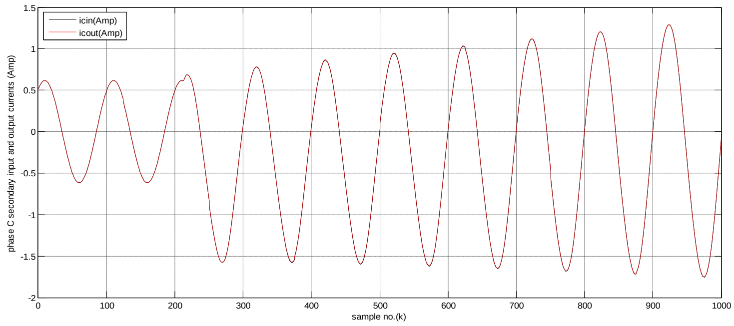
(C) Three Phases Instantaneous Secondary Currents Of Load 2 Feeder.



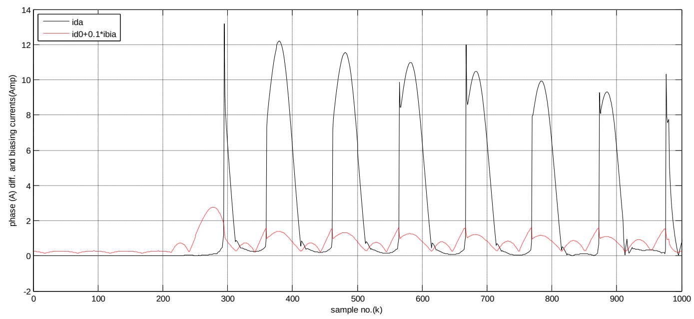
(D) The Two Input And Output Current Signals For Phase *"A", (I_{a1} And I_{a2}).*



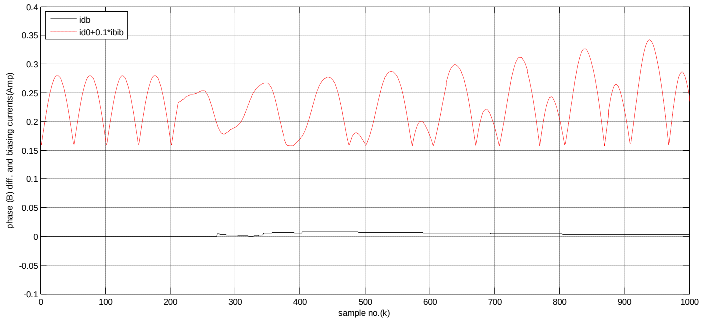
(E) The Two Input And Output Current Signals For Phase *"B", (I_{b1} And I_{b2}).*



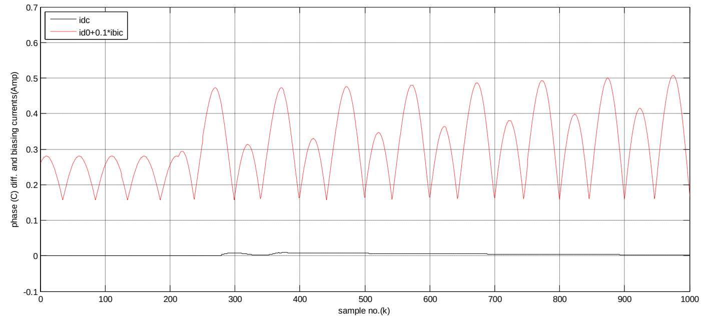
(F) The Two Input And Output Current Signals For Phase *"C", (I_{c1} And I_{c2}).*
Figures 7(A-F) Simulation Current Signals For Case 1.



(A) The Differential Current And The Set Characteristic Equation Signals For Phase *"A", (I_{da} And I_{d0} + 0.1 × I_{bia}).*

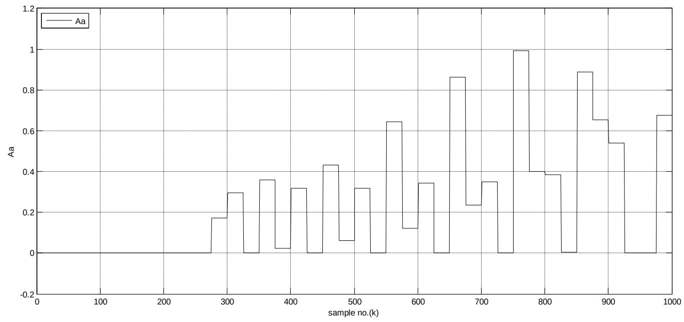


(B) The Differential Current And The Set Characteristic Equation Signals For Phase *"B"*, *(I_{db} And I_{d0} + 0.1 × I_{bib}).*

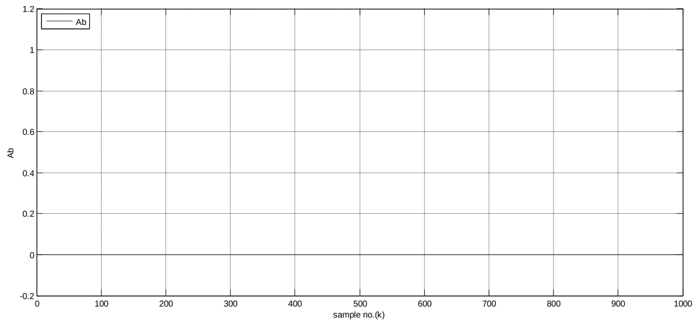


(C) The Differential Current And The Set Characteristic Equation Signals For Phase *"C"*, *(I_{dc} And I_{d0} + 0.1 × I_{bic}).*

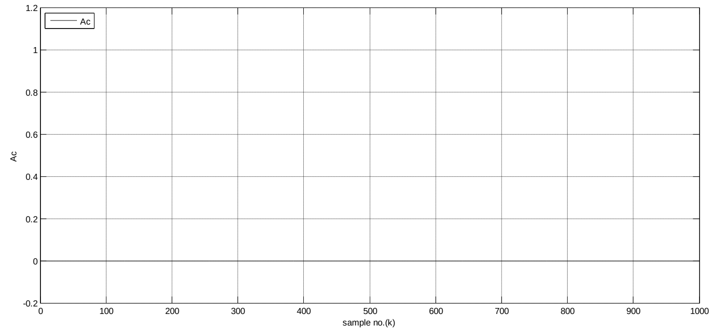
Figure 8(A-C) Response Of Traditional Busbar Differential Relay For Case 1.



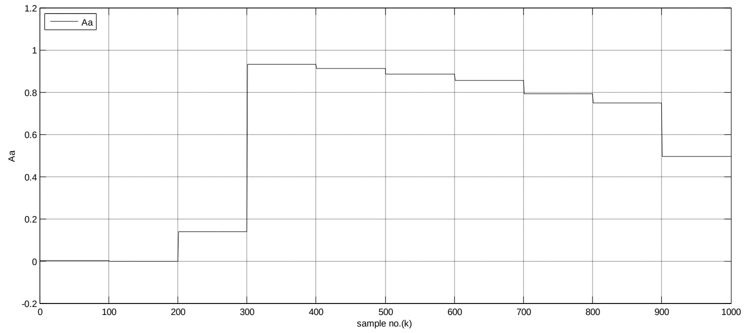
(A) Alienation Coefficients A_a (The Selected Window (M) = 25 Samples/Cycle).



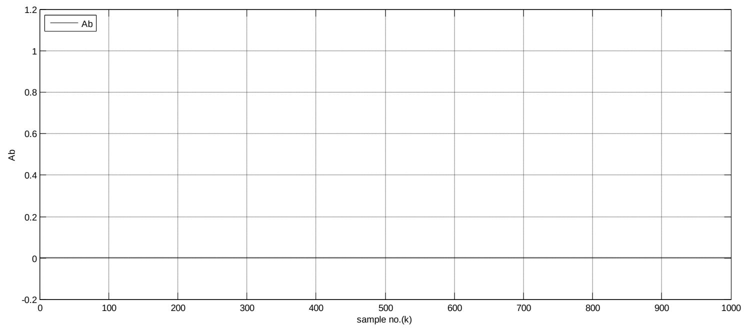
(B) Alienation Coefficients A_b (The Selected Window (M) = 25 Samples/Cycle).



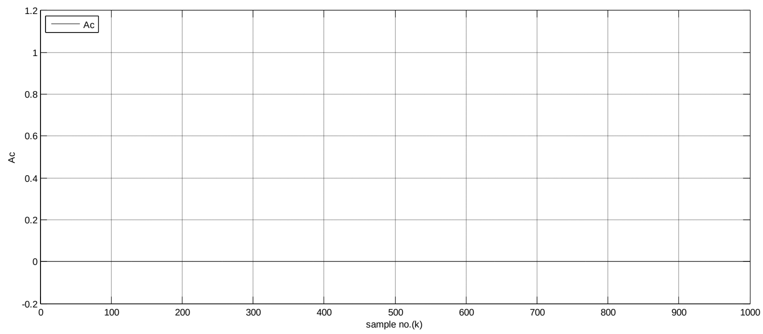
(C) Alienation Coefficients A_c (The Selected Window (M) = 25 Samples/Cycle).
.**Figure 9(A-C)** Response Of Busbar Differential Protection Scheme (Technique 1) For Case 1.



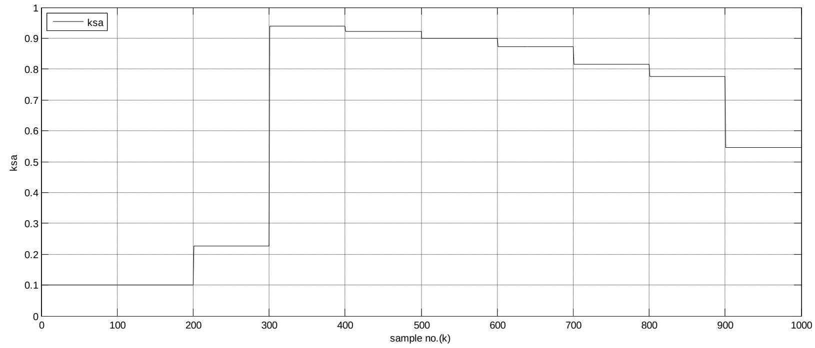
(A) Alienation Coefficients A_a (The Selected Window (M) = 100 Samples/Cycle).



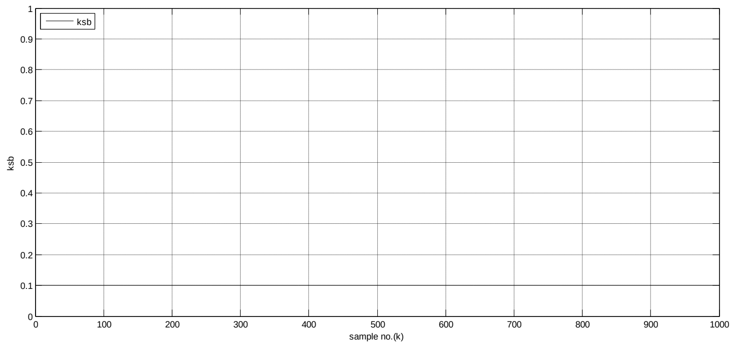
(B) Alienation Coefficients A_b (The Selected Window (M) = 100 Samples/Cycle).



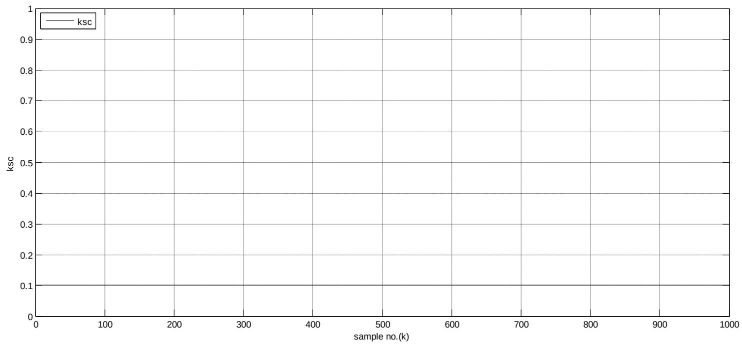
(C) Alienation Coefficients A_c (The Selected Window (M) = 100 Samples/Cycle).



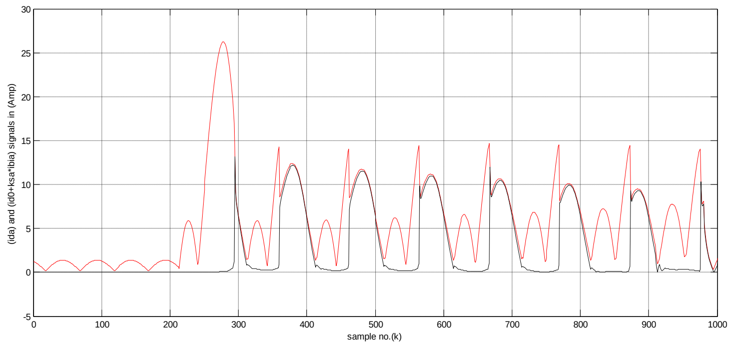
(D)The Suitable Operating Characteristic Slope (K_{sa}) Of Phase (A) Differential Relay.
$K_{sa} = 0.1+0.9\times A_a$



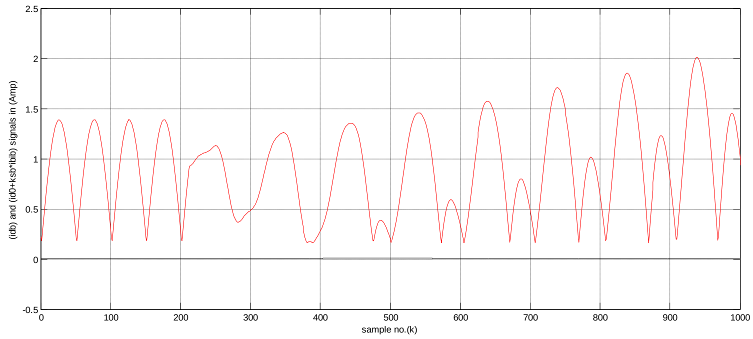
(E)The Suitable Operating Characteristic Slope (K_{sb}) Of Phase (B) Differential Relay.
$K_{sb} = 0.1+0.9\times A_b$



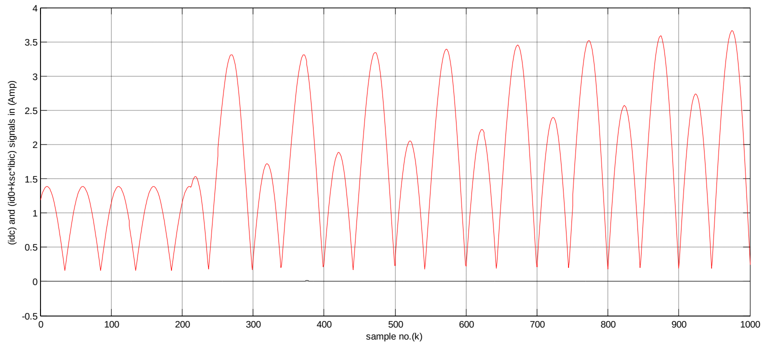
(F)The Suitable Operating Characteristic Slope (K_{sc}) Of Phase (C) Differential Relay.
$Ksc = 0.1+0.9\times Ac$



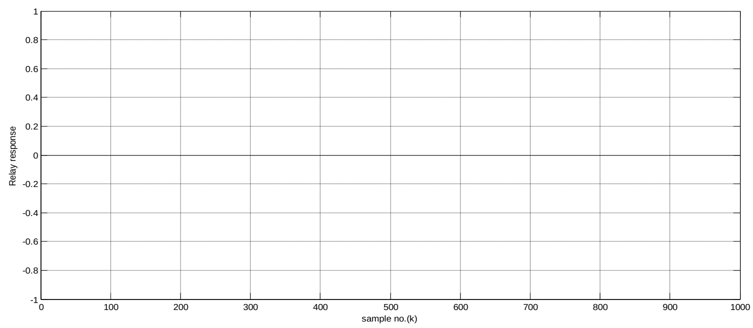
(G) The Differential Current And The Adaptive Characteristic Equation Signals For Phase *"A"*, (I_{da} *And* $I_{d0} + K_{sa} \times I_{bia}$).



(H) The Differential Current And The Adaptive Characteristic Equation Signals For Phase *"B"*, *(I_{db} And $I_{d0} + K_{sb} \times I_{bib}$).*



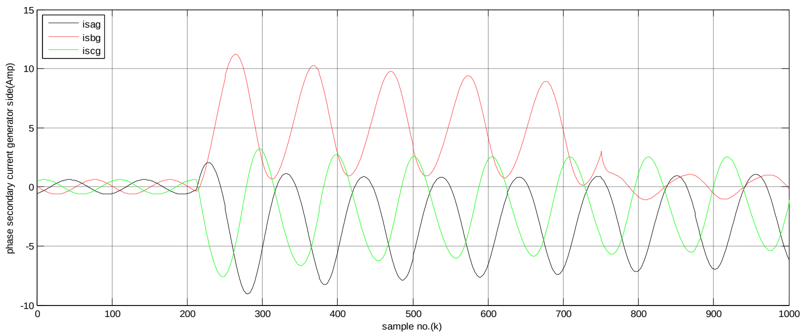
(I) The Differential Current And The Adaptive Characteristic Equation Signals For Phase *"C"*, *(I_{dc} And $I_{d0} + K_{sc} \times I_{bic}$).*



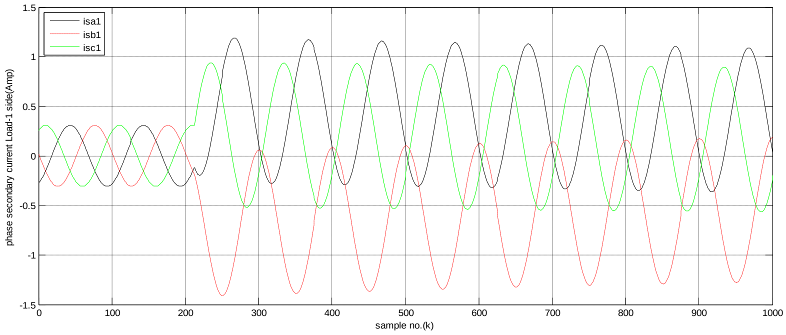
(J) Blocking Trip Signal Of Adaptive Busbar Differential Relay.

Figure 10(A-J) Response Of Busbar Differential Protection Scheme With Adaptive Characteristics (Technique 2) For Case 1.

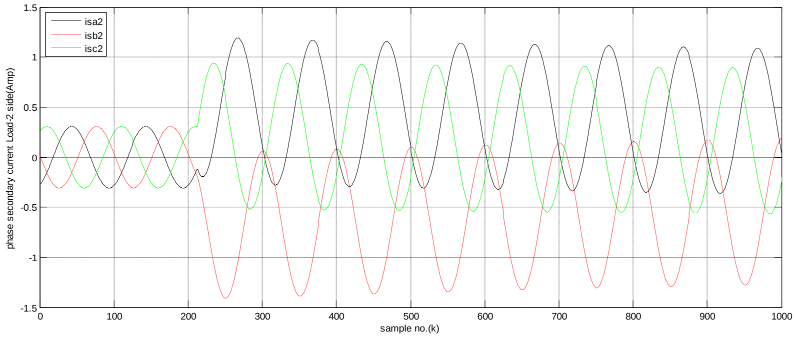
7.2. Case 2: Internal Three Line-To-Ground Fault Without Ct Saturation (R_b = 0.5 Ω For Each Phase Ct)



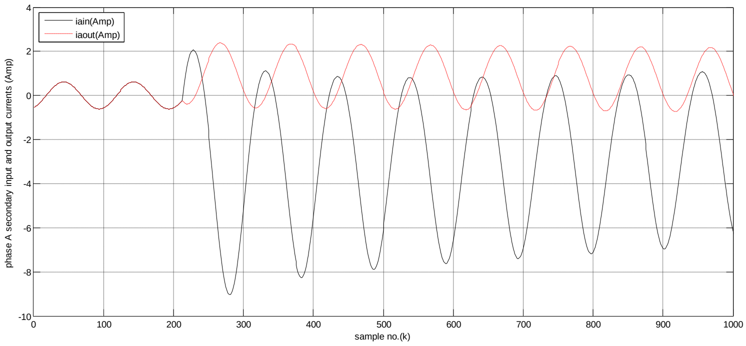
(A) Three Phases Instantaneous Secondary Currents Of Generator Feeder.



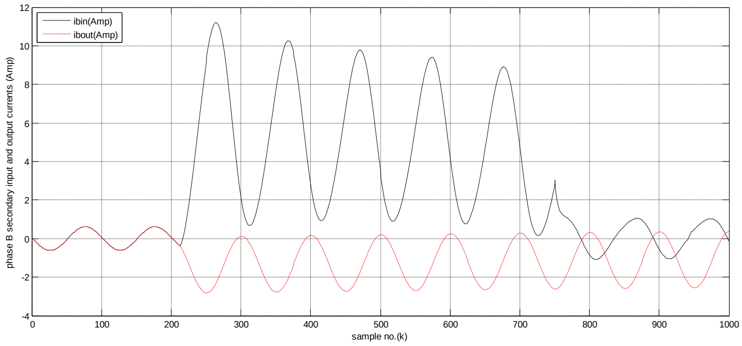
(B) Three Phases Instantaneous Secondary Currents Of Load-1 Feeder.



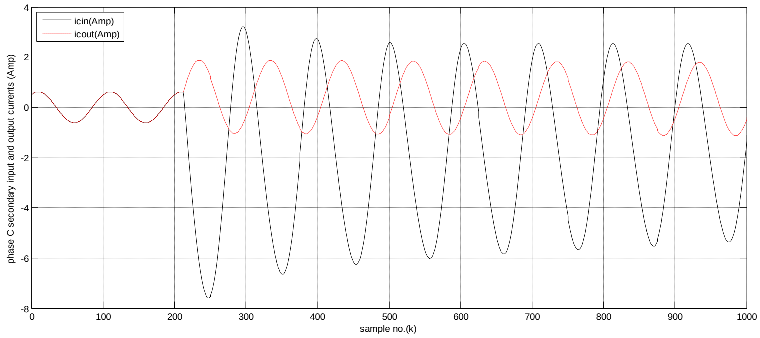
(C) Three Phases Instantaneous Secondary Currents Of Load-2 Feeder.



(D) The Two Input And Output Current Signals For Phase *"A"*, *(I_{a1} And I_{a2}).*

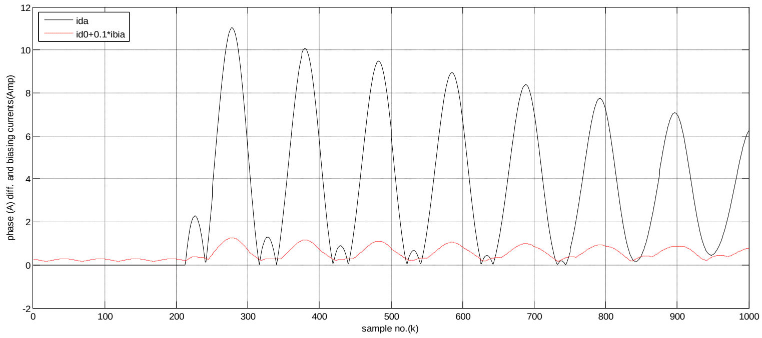


(E) The Two Input And Output Current Signals For Phase *"B"*, *(I_{b1} And I_{b2}).*

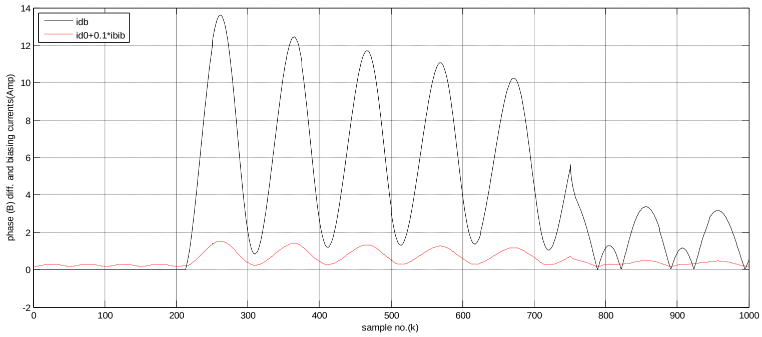


(F) The Two Input And Output Current Signals For Phase *"C"*, *(I_{c1} And I_{c2})*.

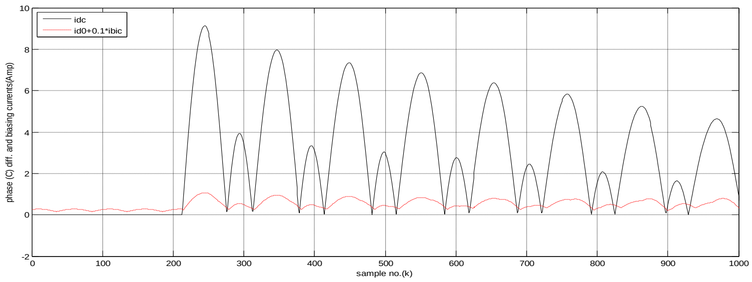
Figures 11(A-F) Simulation Current Signals For Case 2.



(A) The Differential Current And The Set Characteristic Equation Signals For Phase *"A"*, *(I_{da} And I_{d0} + 0.1 × I_{bia})*.

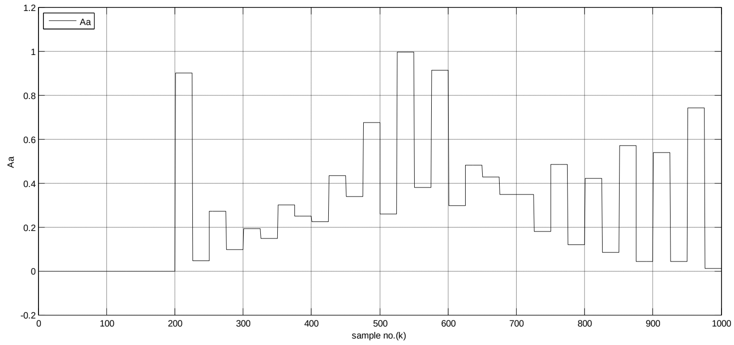


(B) The Differential Current And The Set Characteristic Equation Signals For Phase *"B"*, *(I_{db} And I_{d0} + 0.1 × I_{bib})*.

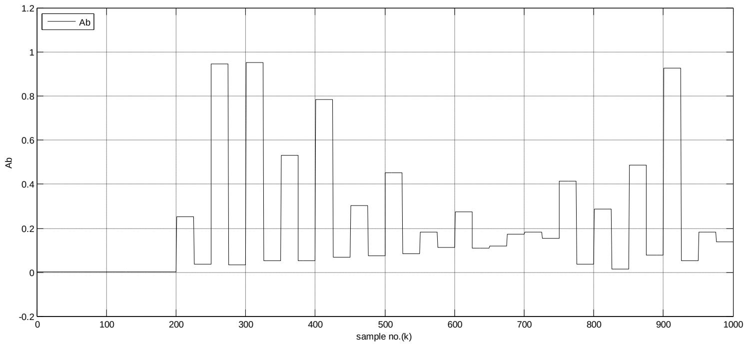


(C) The Differential Current And The Set Characteristic Equation Signals For Phase *"C"*, *(I_{dc} And I_{d0} + 0.1 × I_{bic})*.

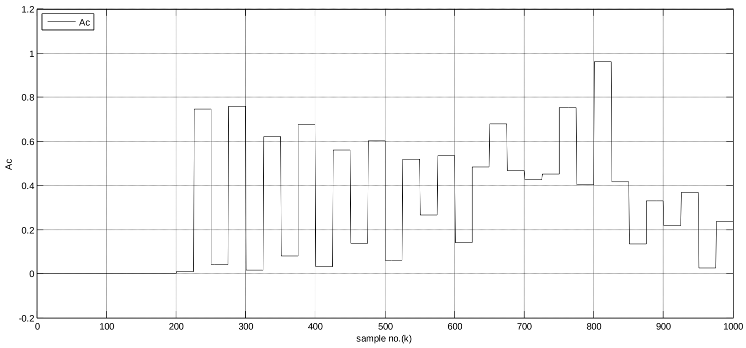
Figure 12(A-C) Response Of Traditional Busbar Differential Relay For Case 2.



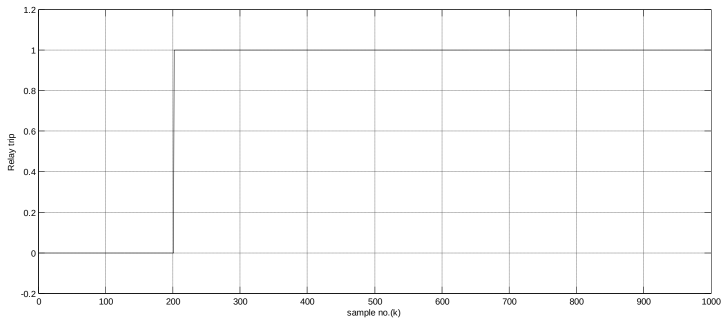
(A) Alienation Coefficients A_a (The Selected Window (M) = 25 Samples/Cycle).



(B) Alienation Coefficients A_b (The Selected Window (M) = 25 Samples/Cycle).



(C) Alienation Coefficients A_c (The Selected Window (M) = 25 Samples/Cycle).



(D) Trip Signal Of Adaptive Busbar Differential Relay.

Figure 13(A-D) Response Of Busbar Differential Protection Scheme (Technique 1) For Case 2.

Table 1 Alienation Coefficient Limits At Different Types Of Faults For The Protected Busbar.

Fault Type	***Alienation Coefficients*** A_x **= 0.05**	***Technique 1 Action***
1.Normal (Healthy) Condition	$A_a \leqslant A_x$, $A_b \leqslant A_x$ And $A_c \leqslant A_x$	*Blocking*
2. External Fault Condition (Without Ct Saturation)	$A_a \leqslant A_x$, $A_b \leqslant A_x$ And $A_c \leqslant A_x$	*Blocking*
3. Internal Fault Condition	$A_a > A_x$, $A_b > A_x$ Or $A_c > A_x$	*Tripping*
4. External Fault Condition (With Ct Saturation)	$A_a \leq A_x$, $A_b \leq A_x$ *And* $A_c \leq A_x$ *During The First One-Eighths (1/8) Cycle After Fault Inception , And* $A_a > A_x$, $A_b > A_x$ *Or* $A_c > A_x$ *After Ct Saturation Beginning*	*Blocking*

Table 2 Lookup Table Of Alienation Coefficients (A_s) And The Suitable Operating Characteristics Slope (K_s) For Adaptive Differential Relay.

A_s	0	0.011	0.022	0.033	0.044	…….	0.955	0.966	0.977	0.988	1
$K_s = 0.1 + 0.9 \times A_s$ *(Step* K_s *= 0.01)*	$K_{min} = 0.1$	0.11	0.12	0.13	0.14	…….	0.96	0.97	0.98	0.99	$K_{max} = 1$

Table 3 The And Logical Rule For Processing The Dual Protection Techniques Of The Suggested Scheme.

Fault Type	***Technique 1***		***Technique 2***	***Relay Action***
1.Normal (Healthy) Condition	*Blocking (0)*		*Blocking (0)*	*Blocking (0)*
2. External Fault Condition (Without Ct Saturation)	*Blocking (0)*		*Blocking (0)*	*Blocking (0)*
3. Internal Fault Condition	*Tripping (1)*		*Tripping (1)*	*Tripping (1)*
4. External Fault Condition (With Ct Saturation)	*Blocking (0)*		*Blocking (0)*	*Blocking (0)*

Table 4 Power System Parameters Data.

Power System Parameter	***Data***
Synchronous Generator (Sending Source)*:*	
Rated Volt-Ampere / Rated Line Voltage / Rated Frequency	*320 Mva / 19.57 Kv / 50 Hz*
Number Of Poles /Neutral Grounding Impedance (R_n)	*2/ 0.77 Ω*
Step-Up Transformer:	
Rated Volt-Ampere	*340 Mva*
Transformation Voltage Ratio	*19 Kv /500 Kv*
Connection Primary/Secondary	*Delta/Star Earthed Neutral*
Primary Winding Impedance (Z_p) *Secondary Winding Impedance* (Z_s)	*0.0027 + J0.184 Ω*
Vector Group	*0.7708 + J 61.8 Ω*
Z%	*Ynd1*
	15%
Transmission Lines:	
+Ve Sequence R	*0.0217 Ω /Km*
Zero Sequence R	*0.247 Ω /Km*
+Ve Sequence Xl	*0.302 Ω /Km*
Zero Sequence Xl	*0.91 Ω /Km*
+Ve Sequence 1/Xc	*3.96 µ℧ /Km*
Zero Sequence 1/Xc	*2.94 µ℧ /Km*
Transmission Line Long (Km)	*200 Km*
Aux. Load (Load 1):	
Load 1 Volt-Ampere	*30 Mva At Pf = 0.85 Lag*
Aux. Load (Load 2):	
Load 2 Volt-Ampere	*30 Mva At Pf = 0.85 Lag*
Power Network (Receiving Source):	
Nominal Line Voltage	*500kv (1pu)*
Voltage Phasor Angle Phase	0^0
Nominal Frequency	*50 Hz*
Volt-Ampere Short Circuit	*25 Gva (* $I_{s.C}$ *= 10 Ka)*
Current Transformer (Ct):	
Ctr	*12000 A/ 1a*
Rated Burden	*30 Va*
R_{burden}	*0.5 Ω*
Class	*5p20*

Table 5 Operating Conditions Of Electrical Components.

Electrical Component **(Operating Condition*)***	***Data***
$F_{operated}$	*50 Hz*
Load 1 (Aux. Load)	*10.85 + J 6.72 Ω*

Load 2 (Aux. Load)	*10.85 + J 6.72 Ω*
Load 3 (Main Load)	*8.5 + J 5.26 Ω*
Generator Operating Power Angle ($Δ_1$)	0^{O}
Operating Phase Peak Voltage Of Generator	*16063 Volt*
Generator Grounding Impedance	*0.0 Ω*

List Of Symbols And Abbreviations, Used In This Paper, Are Illustrated In **Table 6.**

Table 6 List Of Symbols And Abbreviation.

Symbols	Abbreviations
I_{s1} (K)	The Summation Input Current Values At Instant *K* For Phase ''*S*'' Of Busbar.
I_{s2} (K)	The Summation Output Current Values At Instant *K* For Phase ''*S*'' Of Busbar.
I_{sj} (K)	The Sampled Secondary Current Value At Instant *K* For Ct Of Circuit *J* (Where, *J = 1 To 3*)
I_{a1} (K)	The Summation Input Current Values At Instant *K* For Phase ''*A*'' Of Busbar.
I_{a2} (K)	The Summation Output Current Values At Instant *K* For Phase ''*A*'' Of Busbar.
I_{b1} (K)	The Summation Input Current Values At Instant *K* For Phase ''*B*'' Of Busbar.
I_{b2} (K)	The Summation Output Current Values At Instant *K* For Phase ''*B*'' Of Busbar.
I_{c1} (K)	The Summation Input Current Values At Instant *K* For Phase ''*C*'' Of Busbar.
I_{c2} (K)	The Summation Output Current Values At Instant *K* For Phase ''*C*'' Of Busbar.
I_d (K)	The Differential Current Signal At Instant *K* Between Input And Output Current Signals For The Protected Busbar
I_{bi} (K)	The Biasing Current Signal At Instant K For The Protected Busbar
I_d	The Magnitudes Of The Fundamental Component Of Sampled Differential Current $I_d(X)$
I_{da}	The Magnitudes Of The Fundamental Component Of Sampled Phase (*A*) Differential Current $I_{da}(X)$
I_{db}	The Magnitudes Of The Fundamental Component Of Sampled Phase (*B*) Differential Current $I_{db}(X)$
I_{dc}	The Magnitudes Of The Fundamental Component Of Sampled Phase (*C*) Differential Current $I_{dc}(X)$
I_{bi}	The Magnitudes Of The Fundamental Component Of Sampled Biasing $I_{bi}(K)$
I_{bia}	The Magnitudes Of The Fundamental Component Of Sampled Phase (*A*) Biasing $I_{bia}(K)$
I_{bib}	The Magnitudes Of The Fundamental Component Of Sampled Phase (*B*) Biasing $I_{bib}(K)$
I_{bic}	The Magnitudes Of The Fundamental Component Of Sampled Phase (*C*) Biasing $I_{bic}(K)$
S	The Phase Designation *(A, B Or C)*
N_c	The Number Of Circuits (Feeders) Connected To The Protected Busbar $(N_c = 3)$
J	The Circuit Or Feeder Name *(1, 2 Or 3)*
I_{d0}	The Pickup Differential Current Of Differential Relay (The Predetermined Threshold Limit Of Differential Current)
T_d	The Delay Time Of Relay Operation After Fault Occurrence
T_s	The Ct Saturation Period (I.E. Time Instants Of Saturation Beginning And End)
R_a	The Cross-Correlation Coefficient Calculated Between Input And Output Current Signals (I_{a1} And I_{a2}) For The Phase *"A"* Of Busbar.
R_b	The Cross-Correlation Coefficient Calculated Between Input And Output Current Signals (I_{b1} And I_{b2}) For The Phase *"B"* Of Busbar.
R_c	The Cross-Correlation Coefficient Calculated Between Input And Output Current Signals (I_{c1} And I_{c2}) For The Phase *"C"* Of Busbar.
R_s	The Cross-Correlation Coefficient Calculated Between Input And Output Current Signals (I_{s1} And I_{s2}) For The Phase *"S"* Of Busbar.
A_a	The Alienation Coefficient Calculated Between The Two Current Signals (I_{a1} And I_{a2}) For The Phase *"A"* Of Busbar.
A_b	The Alienation Coefficient Calculated Between The Two Current Signals (I_{b1} And I_{b2}) For The Phase *"B"* Of Busbar.
A_c	The Alienation Coefficient Calculated Between The Two Current Signals (I_{c1} And I_{c2}) For The Phase *"C"* Of Busbar.
A_s	The Alienation Coefficient Calculated Between The Two Current Signals (I_{s1} *And* I_{s2}) For The Phase "*S*" Of Busbar.
A_{ab}	The Alienation Coefficient Calculated Between The Two Faulted Phase's Currents For The Input Phase Currents (I_{a1} *And* I_{b1}).
A_{bc}	The Alienation Coefficient Calculated Between The Two Faulted Phase's Currents For The Input Phase Currents (I_{b1} *And* I_{c1}).
A_{ac}	The Alienation Coefficient Calculated Between The Two Faulted Phase's Currents For The Input Phase Currents (I_{a1} *And* I_{c1}).
A_x	Alienation Coefficients Limit.
I_{sag} (K), I_{sbg} (K), I_{scg} (K)	Three Phases Instantaneous Secondary Currents Of Generator Feeder
I_{sa1} (K), I_{sb1} (K), I_{sc1} (K)	Three Phases Instantaneous Secondary Currents Of Load-1 Feeder
I_{sa2} (K), I_{sb2} (K), I_{sc2} (K)	Three Phases Instantaneous Secondary Currents Of Load-2 Feeder
Cos (0^o)	Cosine (Angle Zero)

Ctr	Current Transformer Ratio
F	The Nominal Frequency
H	The Number Of Samples Between The Two Windows Which Are Shifted From Each Other.
C_1 And C_2	The Constants Of Linear Equation
K_s	The Slope Of Each Operating Characteristic For Differential Relay
K_{sa}	The Slope Of Each Operating Characteristic For Phase (*A*) Differential Relay
K_{sb}	The Slope Of Each Operating Characteristic For Phase (*B*) Differential Relay
K_{sc}	The Slope Of Each Operating Characteristic For Phase (*C*) Differential Relay
I_n	The Busbar Nominal Current.
M	The Number Of Samples Per Window To Be Correlated Used In The Algorithm.
R_b	Current Transformer Burden
R_f	Fault Resistance In Ω.
Slg	Single Line-To-Ground Fault.
T_{bb}	Operating Time (In Seconds) For Busbar Protection Function.
ΔI	The Change Of Current Value In The Same Phase Signal.
Δt	The Time Interval Of One Sample.
Ac	Alternating Current
Dc	Direct Current
Ct	Current Transformer
Ct_1	The Current Transformer 1 For Feeder 1
Ct_2	The Current Transformer 2 For Feeder 2
Ct_3	The Current Transformer 3 For Feeder 3
Bb_1	Busbar Number 1(Required To Be Protected)
Bb_2	Busbar Number 2
Bb_3	Busbar Number 3
Cb	Circuit Breaker
Tl	Transmission Line
F_1	Location Of Internal Fault On The Simulated Power System
F_2	Location Of External Fault On The Simulated Power System

II. Conclusions

In This Paper, A New Comprehensive Approach Relies On Dual Protection Techniques Against Various Fault Conditions On Busbar Is Described. The Approach Is Based On Alienation And Differential Concepts For Busbar Protection And Avoiding Current Transformer Saturation Effects, Which Can Significantly Improve Protection Stabilization In Cases Of External Faults Accompanied With Different Ct Saturation Extent. Detailed Algorithms Based On Three Phase Alienation Coefficients For Fault Detection, Faulty Phase Selection, Discrimination Between Internal

And External Faults, Evaluation Of Ct Saturation Degrees, And Selection Of The Necessary Level For Adaptation Of Differential Relay Curves Are Presented. The Developed Adaptive Procedure Includes Appropriate On-Line Modifying Of The Differential Relay Characteristics During Saturation Period Of Current Transformers. Atp/Emtp Software Has Been Used For Generating Fault Data And Then Processed In Matlab To Get An Alienation Coefficient Between Input And Output Currents For Each Phase Of The Protected Busbar. The Three-Phase Coefficients Are Used In The Proposed Protective Scheme To Implement Relay Logic. The Simulation Results Of The Adaptive Procedure Proved Much Better Relay Performance When Compared To The Traditional Relay Version Without Adaptation. The Protective Scheme Is Able To Operate Only For The Internal Faults, And It Remains Stable During External Faults As Well As Normal Load Condition. In Addition, The Results Indicate That The Technique Is Very Effective In Preventing False Tripping During External Fault Conditions With Ct Saturation By Selecting The More Suitable Operating Characteristics Of Differential Relays.

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